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ORBIT ANALYSIS IN RCNP RING CYCLOTRON

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ABSTRACT

For the RCNP ring cyclotron beam behaviors have been calculated by assuming various voltage distributions in the accelerating cavities. The results for the orbit analyses of the longitudinal motion, the radial motion and axial motion are presented for the six-sector ring cyclotron.

INTRODUCTION

The construction of an intermediate energy ring cyclotron to accelerate protons up to 400 MeV has started this year. The ring cyclotron uses an AVF cyclotron which has been operating as an injector. The range of the acceleration frequency for the ring cyclotron is 30-50 MHz. Since the ions are accelerated with higher harmonic RF mode, a flat-topping cavity is used to get larger phase acceptance in the ring cyclotron. This ring cyclotron uses only one flat-topping cavity, and an unbalance of cavity voltages will generate an effect equivalent to the first harmonic field perturbation.

For the acceleration system an 18-degree dee acceleration cavity and a single gap acceleration cavity are taken into account. Previous report[1] shows results for the 18-degree dee acceleration, but now single gap acceleration cavities are used in the ring cyclotron. In the case of 18-degree dee accelerations there is no acceleration for 20th harmonic RF modes, and it is difficult to accelerate ions near 20th harmonic RF mode. This difficulty does not exist for a single gap acceleration. In actual acceleration sixth and tenth harmonic RF modes are used for protons and light ions. For the acceleration of heavy ions with lower energies, higher harmonic RF mode becomes necessary. However for the acceleration of these lower energies the combination of multiply charged ECR ion source and AVF cyclotron is possible, and the use of the ring cyclotron is not necessary. This report summarizes the results for the 18-degree dee accelerations.

LONGITUDINAL MOTION

If proton beam with RF phase width 7 degrees is accelerated to 400 MeV by sinusoidal acceleration voltage, the energy width of 700 keV is generated. This energy broadening can be canceled perfectly with a flat-topping cavity. If the phase errors between the cavities are less than 0.1 degree the energy width of the 400 MeV protons is less than 10^{-4}.

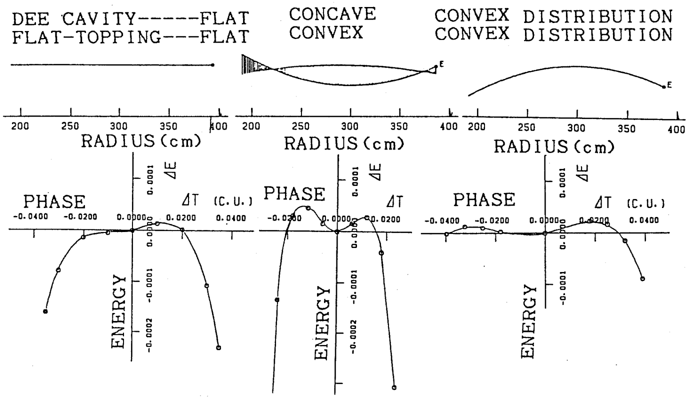

Fig. 1. Energy deviation of the 400 MeV proton beams versus acceleration phases for various radial voltage distributions. a) flat distribution b) concave distribution c) convex distribution

The ratio of the acceleration voltage at extraction to injection radii (V_{ext}/V_{inj}) should not be much larger than one. At the extraction radius the energy width of the injected beam will be multiplied by this ratio. Consequently, large phase compression of beam cannot be expected.

The wide phase acceptance for single turn extraction mode with a flat-topping is desirable to get high intensity beam. The phase acceptance depends much for the radial distribution of the acceleraiton voltage as shown in Fig. 1. Phase acceptance of 20-degree width can be expected for flat voltage distribution (Fig. 1a). In Figs. 1b and 1c the convex distribution is assumed for the flat-topping cavity. In case of the concave distribution for the acceleration cavities, the beam phase width expands as the dee voltages decrease in mid course of the acceleration and the beam energy gain is small for early and late phases. At the extraction radius the dee voltage recovers to that at injection radius, and the beam phase width compresses to original value. The concave distribution has a narrower phase acceptance. In the case of convex distribution for the acceleration cavities, the beam phase width compresses as the dee voltages increase in mid course of the acceleration and the beam with wider phase width at the injection can be accelerated within the flat-topping region of the acceleration phase but with larger energy width at each phase. At the extraction radius the dee voltage decreases to that at injection radius and beam phase width expands with the recovery of energy width at each phase. As a result a wide phase acceptance can be realized by the convex distribution as shown in Fig. 1.

Because of spiral magnets acceleration cavities are tilt. The calculations of the accelerated orbits usually used tilt angle of 5.164 degrees for all cavities. In mid course of the acceleration the energy width of beam becomes larger as shown in Fig. 2. However, by adjusting the RF phase of the flat-topping cavity it is possible to minimize the energy width at the extraction radius. The ions accelerated with different phases have almost the same radii for the same turns at an angle calculated, and it is expected to get well separated turns on the measurements by a radial differential probe if a suitable angle for the probe is chosen. Computer calculations can show that this minimum of the energy width at the extraction radius exists by trial and error. It is interesting whether actual beam adjustment shows similar situations or not. If the tilt angle of the flat-topping cavity is changed to 4.924 degrees and other dee cavities are set to 5.164 degrees we can get both small energy width and radial width in mid course of the acceleration and also at the extraction radius. An example of this calculation is shown in Fig. 3.

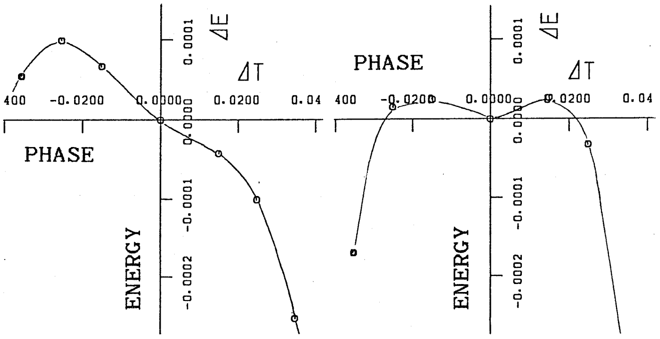

Fig. 2. Energy deviation in the 400 MeV alpha particle acceleration. In mid course of the acceleration the energy width of beam becomes larger.

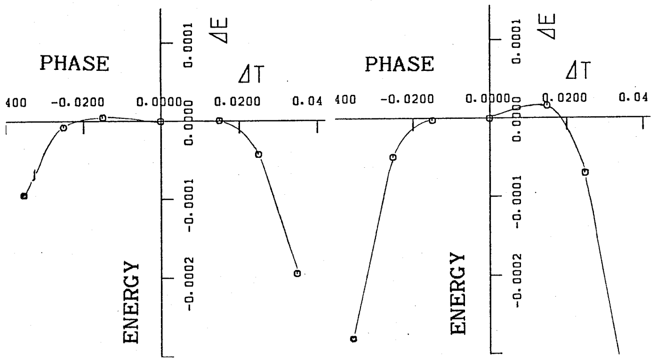

Fig. 3. Energy deviation in the 400 MeV alpha particle acceleration. If the tilt angle of the flat-topping cavity is changed, both small energy width and radial width in mid course of the acceleration and at the extraction radius are obtained.

RADIAL MOTION

Protons are accelerated through $\nu_r=6/5$ resonance. The 400 MeV protons cross $\nu_r=6/4$ resonance at radius near extraction. As expected from its order, the effect of $\nu_r=6/5$ resonance is relatively small. The radial phase ellipse of the accelerated proton beam was traced from the injection radius to the extraction radius, but no remarkable deformation of the phase ellipses is observed in numerical calculation. A radial oscillation of corrected magnetic field produced by using trim coils is simulated by the superposition of a periodic field component with a constant amplitude and a constant period. This modulates the betatron frequencies ν_r and ν_z. Figure 4 shows the relation of ν_r and ν_z for 207 MeV proton acceleration. In this case the betatron frequencies ν_r and ν_z for the isochronous field are nearly equal. Figure 5 shows a radial phase plot of 207 MeV proton acceleration with the radial

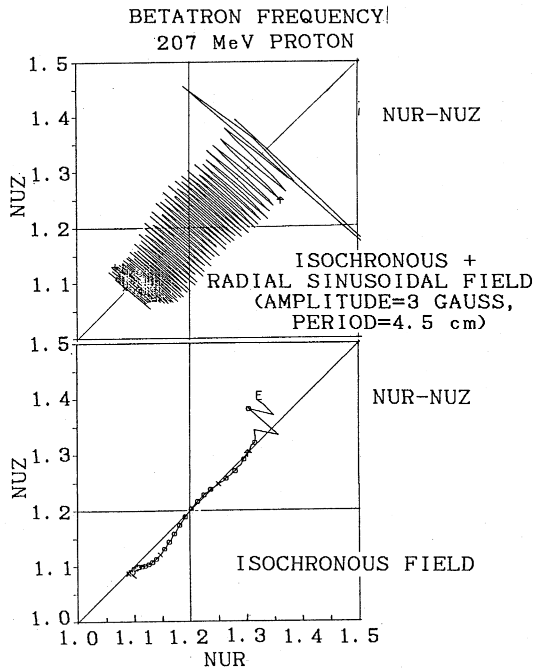

Fig. 4. The betatron frequencies for 207 MeV proton acceleration. The values of ν_r and ν_z for the isochronous field are nearly equal.

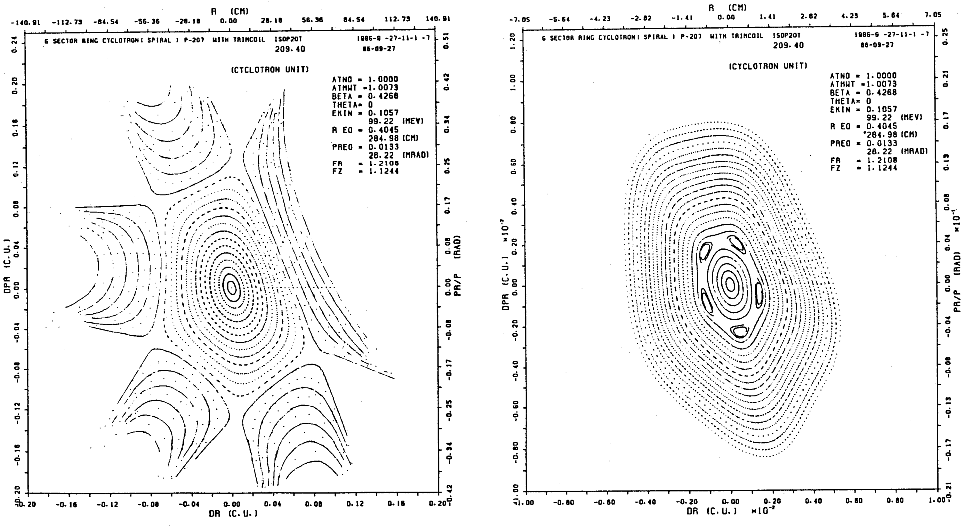

Fig. 5. Radial phase plot of 207 MeV proton acceleration. The magnetic field is assumed to include radial sinusoidal field with amplitude 3 Gauss and period 4.5 cm.

periodic field. Figure 5a is the phase plot covering a large amplitude oscillation. A stable region is quite large, and the fixed points of ν_r=6/5 resonance and separatrix lines are located 40 cm aprt from the equilibrium orbit. Figure 5b expands the center region of Fig. 5a. Here, five islands and corresponding fixed points of ν_r=6/5 resonance appear again at only 1 cm apart form the equilibrium orbit. The fixed points outside the stable region appear from the global characteristics of the field distribution, and move slowly with ion energy on the phase plot. The fixed points around the equilibrium orbit appear from the local rapid variation of the field, and move around the equilibrium orbit.

Introducing a flat-topping cavity increases the amplitude of radial betatron oscillation, but this growth is suppressed by a rearrangement of the cavity voltages and an adjustment of the first harmonic field.[2] The detailed analysis is reported in a separated paper.

Many trim coils are used to produce an isochronous magnetic field. To minimize the difference between the ideal isochronous field and the corrected field with trim coils, it is desirable to increase the number of trim coils as many as possible. However this correction produces a radial sinusoidal periodic component in magnetic field. Starting from an accelerated equilibrium orbit at some radius, an ion orbit was calculated forward and backward to get accelerated orbit. When a radial increase in $1/(\nu_r-1)$ revolutions coincides with the period of radial sinusoidal field, a computer result shows a growth of radial oscillation. The radial position of this resonance depends on the acceleration voltage. Higher voltage shifts the position of resonance to larger radius.

After seven to ten periods of the radial betatron oscillation a growth of resonance amplitude stops. The final amplitude depends on the voltage of flat-topping cavity, and the resonance disappears without flat-topping cavity or by using two flat-topping cavities that confronts each other. By introducing force to shift an orbit center with the first harmonic field perturbation or to put different voltages to three delta-type cavities, the accelerated particles cross the resonance. This fact suggests a method to compensate the resonance by adjusting the accelerating voltage of cavities or generating the first harmonic field by using harmonic coils. A computer calculation shows this cancellation for a trace of ion, but for an ion of different beam phase the cancellation is not complete because of the different dependence on the beam phase. Further investigations by means of the calculation and the actual beam acceleration may be necessary.

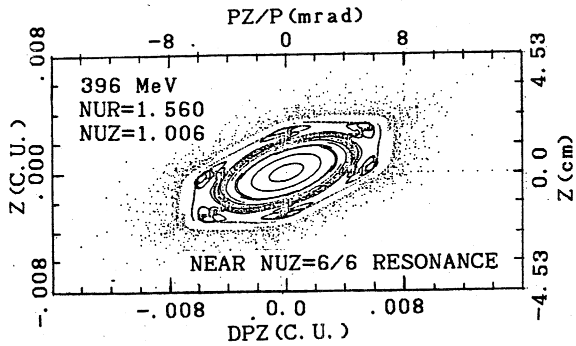

Fig. 6. Axial phase plot of the 400 MeV protons near ν_z=6/6 resonance.

AXIAL MOTION

To investigate the size of the stable region in the axial motion of particles static phase plot in the (z,p_z) plane was used. The axial phase plots have been obtained from four dimension (r,p_r,z,p_z) calculations. Therefore, it is necessary to display clear plots by choosing suitable initial conditions. At first the axial phase plots have been obtained by trial and error. The radial component (r,p_r) of the starting point was chosen on an equilibrium orbit, and either of p_z or z component sets to non-zero value. In some case (r,p_r) values of traced particles shift from the equilibrium value after many revolutions, and the projected (z,p_z) phase plots do not lie on a sharp line but fill a narrow band region. Especially these deviations are large for the plots within isolated islands in both (r,p_r) and (z,p_z) planes. This tendency is remarkable when the starting points of (r,p_r) values are set far from the equilibrium orbit.

The axial betatron frequency for the acceleration of 400 MeV protons always lie near ν_z=6/6 resonance. These phase plots near the extraction region is shown in Fig. 6. A numerical study uses magnetic field values expanded in powers of z. If in the magnetic field the terms higher than first order in z are neglected, axial phase plot does not show ν_z=6/6 resonance. If z^2 terms is added in the magnetic field, axial phase plot seems to indicate the existence of the resonance. If terms up to sixth order in z are added in the magnetic field, axial phase plot shows six islands related to ν_z=6/6 resonance. The figure shows a small stability region of height less than 2 cm.

The ions except high energy protons cross ν_z=6/5 resonance and heavy ions are accelerated up to ν_z=6/4 resonance region. The axial phase plot of $^{20}\mathrm{Ne}^{5+}$ ions shows clearly the existence of ν_z=6/4 resonance as shown in Fig. 7. By introducing two sector magnet misalignments the phase plot can indicate the fixed points and islands of ν_z=6/5 resonance. These resonances are weak, and no axial growth is seen in an accelerated orbit calculation.

The 207 MeV protons are accelerated along the coupled resonance $\nu_r=\nu_z$ (and $2\nu_r=2\nu_z$), but the accelerated orbit studies with the displacement of (r,p_r,z,p_z) values from an equilibrium orbit give no indication of this coupled resonance.

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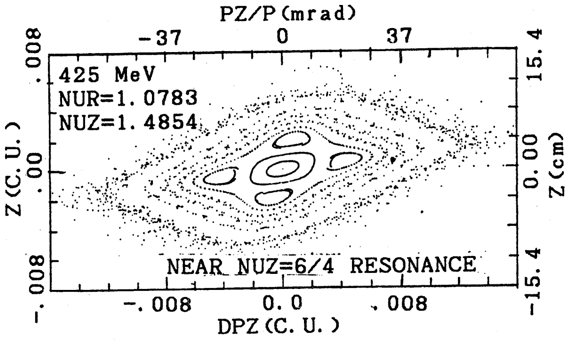

Fig. 7. Axial phase plot of the 425 MeV Neon-20(5+) ions near ν_z=6/4 resonance.